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Professor T. C. McGill

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Applied Physics
California Institute of Technology
Pasadena, CA 91125

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The focus of this research project was to investigate the basic properties of InAs/GaInSb interfaces and how those properties effect the control of growing abrupt interfaces. STM and SIMS studies showed that InAs grown on GaSb tends to be less abrupt because the GaAs bond strengths are stronger than in GaSb. The As in InAs exchanges with underlying Ga atoms, while the displaced Sb is incorporated in the InAs. Atomic-layer epitaxy at higher temperatures tends to yield smoother interfaces. Electron spectroscopy for chemical analysis (ESCA) was used to determine band offsets at InAs/GaSb interfaces; the offset was 90 meV higher for InAs on GaSb than for the reversed order. The end result was an improved recipe for high-quality structures for infrared devices.

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CALIFORNIA INSTITUTE OF TECHNOLOGY

APPLIED PHYSICS 128-95
PASADENA, CALIFORNIA 91125 USA

T. C. McGill
Fletcher Jones Professor
of Applied Physics
Telephone (626))395-4849
Fax (626)568-8972
E-mail tcm@ssdp.caltech.edu
http://www.ssdp.caltech.edu

October 16, 1997

AFOSR
110 Duncan Avenue, Suite B115
Bolling Air Force Base
Washington, DC 20332-0001

ATTN: NE

Ladies and Gentlemen:

Please find attached the final report for AFOSR Grant No. F49620-93-1-0258 entitled **"In and Sb Based III-V Microstructures with Novel Electronic Properties".**

Thank you for your patience as we prepared this final report.

Sincerely

T. C. McGill

T. C.McGill

Enclosure: Original and Two Copies of the AFOSR Final Report.

FINAL REPORT

Title: ***In and Sb Based III-V Microstructures with Novel Electronic Properties***

AFOSR Grant No. F49620-*93-1-0258*

PI: Professor T. C. McGill

Address: MS 128-95
California Institute of Technology
Pasadena, CA 91125

Telephone: (626)395-4849

Fax: (626)568-8972

E-mail: tcm@ssdp.caltech.edu

Period Covered: 4/1/93-6/30/97

Project Manager: Major Michael W. Prairie, Ph. D.

Air Force Office of Scientific Research

Bolling AFB, DC 20332-0001

Research Objectives

We carried out a research program aimed at the most promising material for satisfying the Air Force's needs for infrared imaging from space. This application is very demanding, requiring long wavelength response, the highest possible operating temperature, the highest performance, large number of pixels and integrated processing electronics.

- We investigated the basic properties of InAs/GaInSb superlattices.
- We investigated the basics of this anion switch with an eye to producing a recipe that will produce adequate control.
- We employed *in situ* reflection high energy electron diffraction (RHEED). The images were captured electronically and processed with a workstation to obtain information on the properties of the superlattice interfaces.
- Electron spectroscopy for chemical analysis (ESCA) was employed to measure the chemical composition of the growth surfaces.
- Scanning tunneling microscopy was employed to investigate the growth surface on a microscopic scale.
- This research has resulted in a growth recipe that will provide the Air Force with its unique needs for an infrared material.

Status of Effort

The effort has arrived at the end of the funding. Like all research programs it is not completed. The STM/BEEM experiments could be carried much further to probe the dissimilarities of InAs/GaInSb interfaces versus GaInSb/InAs. It is widely recognized that these two interfaces are very different. Further the variations due to variations of lateral composition have not been probed at all. BEEM/STM could provide information on this subject

New Findings

The research program accomplished all of its aims.

- InAs-on-GaSb is less abrupt
    - As exchange down into GaSb because the bond strengths:GaAs>GaSb
    - Source of free As during interface formation
    - Sb incorporation up into InAs
    - Sb->good surfactant
- GaSb-on-InAs is more abrupt
    - Sb does not exchange into InAs
    - Bond strengths: InSb<InAs
    - As does not ride up
    - As less of a surfactant
- Atomic Layer Epitaxy (ALE) and higher growth temperatures give
    - Smoother interfaces
    - More symmetric interfaces
    - Less Sb incorporation in InAs overlayers
    - Less Sb incorporation in InAs overlayers
- Band Offsets Dependent on Parameters of the Growth
    - InAs on GaSb valence band offset not dependent on the interface composition

- •InAs/GaSb valence band offset dependent on the growth order

- •InAs on GaSb has larger band offset by 0.09eV as determined by ESCA

•XPS data shows the expected composition dependence

- •GaSb-on-InAs: XPS data and calculation are consistent with an abrupt interface

- •InAs-on-GaSb: Calculation shows that the range of experimental data is NOT consistent with an abrupt interface.Evidence for intermixed anion sublattice

•SIMS data shows

•Direct evidence of Sb incorporation in InAs overlayers

- •Interface grown at higher temperature is more abrupt: consistent with STM observations, high temperature favors formation of equilibrium InAs bonds over metastable InSb bonds

- •Lower interface has more abrupt Sb profile hence result is not an artifact of sputter roughening

•BEEM Measurements on InAs/AlSb/InAs/AlSb/InAs

- •See Threshold for AlSb Barrier

- •Variation in Threshold Across Sample ±0.05V

Personnel Supported

•Faculty: Professor T. C. McGill

•Graduate Students: Robert Miles, and Xiao-Chang Cheng

•Undergraduate:None

•Other: Douglas A. Collins (Postdoctoral Fellow), David Z. Ting (Senior Postdoctoral Fellow)

Publications

The publications are listed below. The number is the publication number for the group should the paper be requested.

351. "RHEED Studies of the Growth of $InAs/Ga_{1-x}In_xSb$ Strained-Layer Superlattices.", D. A. Collins, T. C. Fu, T. C. McGill, J. Vac. Sci. Technol. B10(4), 1779-1783 (Jul/Aug 1992).

361. "Prospects for the Future of Narrow Band Gap Materials.", T. C. McGill, D. A. Collins, Semicond. Sci. Technol. 8, S1-S5, (1993).

365. "XPS Investigation of the Mixed Anion GaSb/InAs Heterointerface.", M. W. Wang, D. A. Collins, T. C. McGill, R. W. Grant, J. Vac. Sci. Technol. B 11(4), 1418-1422 (Jul/Aug 1993).

367. "RHEED Observation of Anion Eschange Reactions on InAs Surfaces.", D. A. Collins, M. W. Wang, R. W. Grant, T. C. McGill, J. Appl. Phys. 75(1), 259-262 (1994).

371, "RHEED Observation of Exchange Recation Dynamics on InAs Surfaces.", D. A. Collins, M. W. Wang, R. W. Grant, T. C. McGill, J.Vac.Sci.Technol. B 12(2), 1125-1128. (Mar/Apr 1994).

376, "Interface Roughness and Asymmetry in InAs/GaSb Superlattices Studied by Scanning Tunneling Microscopy.", R. M. Feenstra, D. A. Collins, D. Z.-Y. Ting, M.W. Wang, T. C. McGill, Phys. Rev. Letters 72 (17) 2749-2752 (25 April 1994).

378, "Cross-Sectional Scanning Tunneling Microscopy of III-V Semiconductor Structures.", R. Feenstra, A. Vaterlaus, J. M. Woodall, D. A. Collins, T. C. McGill, , , Mat.Res.Soc.Symp.Proc. Vol. 332, 15-23, (1994).

379, "Scanning Tunneling Microscopy of InAs/GaSb Superlattices: Subbands, Interface Roughness, and Interface Asymmetry.", R. M. Feenstra, D. A. Collins, D. Z.-Y. Ting, M. W. Wang, T. C. McGill, J. Vac. Sci.Technol. B 12(4), 2592-2597, (Jul/Aug 1994).

389, Three dimensional quantum transport simulations of transmission fluctuations in a quantum dot, S.K. Kirby, D.Z.-Y. Ting, T. C. McGill, Proceedings of the NATO ASI, ed. by D.K. Ferry (Plenum, New York,1995).

408, Mapping of $Al_{(x)}Ga_{(1-x)}As$ Band Edges by BEEM Spectroscopy, X-C. Cheng, D. A. Collins, T. C. McGill, J-VAC-SCI-A v15 (4) : pp2063-2068 (1997 Jul-Aug).

Presentations

Numerous presentations were made at conferences such as the Physics and Chemistry of Compound Semiconductor Interfaces, the International Conference on Narrow Bandgap Materials, and a Nato Advanced Summer School on Quantum Transport in Ultrasmall Devices. We made presentations at two AFOSR Workshops on the AFOSR Program (8/96 and 8/97).

Interactions

The group has a close interactions with Hughes Research Laboratories, notably David Chow and Richard Miles. They are both engaged in growth of devices based on InAs/GaSb/AlSb heterojunctions.